THE REDISCOVERY OF TIME

by Ilya Prigogine

Abstract. Central among problems in cosmology is the crucial question of the articulation of natural and historical time: how is human history related to natural processes described by science? A deterministic world view in which natural processes are reversible, as emphasized by classical Western science, is obviously not the answer. Recent research in fields such as far-from-equilibrium thermodynamics and statistical mechanics reveals irreversibility in natural processes and allows us to explore new forms of dialogue between science and the humanities.

In the preface to the 1959 edition of *The Logic of Scientific Discovery*, Karl Popper states that "there is at least one philosophic problem in which all thinking men are interested. It is the problem of cosmology: the problem of understanding the world—including ourselves, and our knowledge, as part of the world" (Popper 1977). It is obvious that the meaning of time plays an important role in the problem so beautifully spelled out by Popper. It is therefore important to stress the fact that our vision of nature is at present undergoing a radical change toward the multiple, the temporal, and the complex. Until recently, a mechanistic world view dominated Western science, a view according to which the world appeared as a vast automaton. We now understand that we live in a pluralistic world, whose description involves elements not included in the traditional picture.

It is true that there are phenomena that appear to us as deterministic and reversible, such as the motion of a frictionless pendulum or the motion of the earth around the sun: reversible processes do not know any privileged direction of time. But there are also irreversible pro-

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cesses, which involve an "arrow of time." If we bring together two liquids such as water and alcohol, they tend to mix in the forward direction of time, that is, in our future. We never observe the reverse process, the spontaneous separation of the mixture into pure water and pure alcohol. Mixing is therefore an irreversible process; all chemistry involves such irreversible processes.

Today we are becoming more and more conscious of the fact that on all levels, from elementary particles to cosmology, randomness and irreversibility play an ever-increasing role: science is rediscovering time. This obviously introduces a new dimension into the old problem of the two cultures: the relation between the sciences and the humanities.

In a recent lecture (Prigogine 1983), I emphasized that most of European modern philosophy, from Immanuel Kant to Alfred North Whitehead, appears as an attempt to overcome in one way or another the necessity of a tragic choice between the mechanical view of classical physics and our daily experience of the irreversible and creative dimension of life; on this matter I could only confirm the views expressed by Ivor Leclerc (1972): "In our century we are suffering the consequences of the separation of science and philosophy which followed upon the triumph of Western physics in the eighteenth century" (see also Prigogine 1975).

However, I believe the situation today is much more favorable in the sense that the recent rediscovery in physics of time leads to a new perspective. Now the dialogue between hard sciences on one side and human sciences and philosophy on the other may become again fruitful, as it was during the classical period of Greece or during the seventeenth century of Isaac Newton and Gottfried Leibniz.

To illustrate this coming together on a fundamental question, let us consider in this essay the relation between *Being and Time*, to take up the title of the influential essay of Martin Heidegger (1927). This relation may probably be considered as one of the central themes of Western philosophy; the aim of my essay is precisely to point out that today we can envisage a fresh approach. Obviously, this relation does affect large parts of epistemology, and even ontology. While I do not feel prepared to discuss the theological issues, I believe that such a discussion will always be bound to encompass the new concepts science offers us about our position in nature; theological questions are unavoidably related to a discussion of the problem of Being and Time, or Being and Becoming.

Irreversibility

Let us start with a brief summary of the way in which time was described in classical physics. Since Aristotle, Western scientific tradition has taken for granted that time is closely related to motion and therefore to space. As a consequence of this view, we have inherited the idea of an isomorphism between time and a one-dimensional space, as shown in the classical representation of time in which the present separates the past and the future (see fig. 1). This description is used in classical physics as well as, with minor modifications, in quantum theory and in relativity theory. While immensely useful, it does not do justice to the various meanings of time. Past seems to disappear in the present; present disappears in the future. No intrinsic connection appears between past, present and future.

FIG. 1.—A traditional representation of the present separating past and future.

Both our conscious experience and the existence of an evolutionary, time-irreversible universe seem to point to a far richer and subtler concept of time. We may imagine that at present we are sitting on a hill. How does it happen that we glide down always in the same direction? Why do we all age together?

Therefore, we have to reconsider the meaning of time. This, as is well known, was the conclusion reached by Henri Bergson, Whitehead, Edmund Husserl and Heidegger, to name only some of the most profound modern thinkers. However, in contrast with their approach, I want to show here that a new concept of time can be generated from within modern science and that this does not imply a complete break with the scientific tradition of the West.

Already Aristotle associated time with generation and corruption—in our modern language with qualitative change not reducible to local motion. But it was only recently that this aspect of time could be expressed in precise mathematical form. Let us start with the question of irreversibility, which is most closely connected with the problem of evolution.

The difficulties in understanding irreversibility show up very clearly in the classical approach of Ludwig Boltzmann (Prigogine and Stengers 1984; Nicolis and Prigogine 1977; Prigogine 1980). Let us consider the entropy S, the basic quantity which, according to the second law of thermodynamics, increases in isolated systems as the result of irreversible processes. Boltzmann's great idea was to express S in terms of a probability P; this is the content of his celebrated formula

$$S = k \log P \tag{1}$$

Here k is an universal constant, the so-called Boltzmann constant. As follows from this formula, in isolated systems, entropy S increases because the probability increases. At thermodynamic equilibrium, complete disorder is reached and the probability is maximum.

Boltzmann's formula is certainly one of the most important of theoretical physics. While I have no intention of going into the controversies to which it has led, I still would like to emphasize a basic conceptual difficulty imbedded in Boltzmann's attempt. In modern probability theories a fundamental role is played by the so-called transition probability to go at time t from one point, say ω_0, to a region E in phase space (see fig. 2). Suppose our basic description is in terms of trajectories, as is the case in classical mechanics, then this transition probability is equal to one if the domain E contains the trajectory at point t and is equal to zero otherwise. In a genuine probability theory, however, this is not so. Then, the numbers associated with transition probabilities are positive numbers between zero and one. How is this possible? We come immediately to a dilemma.

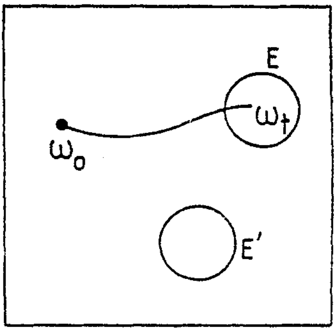

FIG. 2.—Transition probabilities from ω_0 to E is equal to one if domain E contains ω_t. Transition probability to E' is equal to zero.

There are two possible ways of resolving the dilemma. One is to refer to our ignorance: we do not know which trajectory to consider and, as a result, we have to give a statistical weight to various possible trajectories. Such an interpretation would make our ignorance responsible for the appearance of probabilities and ultimately for the introduction of irreversibility in Boltzmann's scheme. However, it is difficult to reconcile this interpretation with the constructive role of irreversibility. We know today that irreversibility is at the root of self-organization in chemistry and physics and that it plays a central role in biological processes (Landsberg 1982). Therefore, life cannot be the outcome of our own errors or of our ignorance.

The only other possibility which seems open is that, for systems to which the second law of thermodynamics applies, the description of reality in terms of trajectories has to be given up. This is obviously a momentous step, and one can understand why great scientists such as Albert Einstein have been reluctant to take it.

However, the conflict between fundamental dynamical theories—be it classical dynamics, quantum mechanics, or relativity—and the second law of thermodynamics is unavoidable. In all these fundamental theories entropy is strictly conserved as a result of a general mathematical property which is the unitary character of the time evolution. Therefore, it seems that, indeed, at the fundamental level of description there exists in classical theoretical physics no place for history, for meaningful changes from order to disorder or vice versa.

P. T. Landsberg discussed this situation in a recent book whose title I find quite appropriate, *The Enigma of Time* (1982). He summarizes some of the positions taken by physicists in the past. For some, probably the majority of physicists, the second law has been regarded as an approximation, or even as anthropomorphic in its character. I already mentioned why this seems quite unlikely today. For others irreversibility comes ultimately from cosmology and perhaps from some gravitational correction to be introduced into the equations of motion. This also seems to be quite unlikely. While it is true that we are embedded in an expanding universe, the second law of thermodynamics is not universal. We may imagine dynamical systems such as the undamped harmonic oscillator of the two-body planetary motion to which we cannot apply the second law; nevertheless, these systems are also embedded in the expanding universe. Moreover, classical dynamics or quantum mechanics have been verified experimentally in simple situations to such a degree of precision that the inclusion of additional terms which would be responsible for thermodynamic irreversibility seems out of question.

For these reasons, we have taken a quite different approach to the problem of irreversibility. We have taken the law of entropy and therefore the existence of an arrow of time as a fundamental fact. Our task then is to study the fundamental change in the conceptual structure of dynamics which results from the inclusion of irreversibility. This fundamental change, as we shall see, is precisely related to a revision of the concepts of space and time, whenever irreversibility is involved.

Let us observe that, curiously, the two great revolutions in physics over the century have been precisely connected with the inclusion of impossibilities in the frame of physics. In relativity a fundamental role is played by the velocity of light which limits the speed at which we may emit signals. Similarly Max Planck's constant h limits the possibilities of measuring simultaneously position and momentum. As noticed by Fritz Rohrlich, "The implications of the finiteness of Planck's constant

($h > 0$) for the quantum world are as strange as the implications of the finiteness of the speed of light ($c < \infty$) for space and time in relativity theory. Both lead to realities beyond our common experience that cannot be rejected" (Rohrlich 1983).

In addition to the impossibilities which are the result of Planck's constant or of the finiteness of the speed of light, we have the impossibilities which come from irreversibility, the second law of thermodynamics. Only processes which increase entropy in isolated systems are possible. Such a limitation on the macroscopic scale must express also some type of limitation on the microscopic scale. Therefore, the second law must appear, as we shall see, as a kind of selection principle propagated by dynamics. The inclusion of this supplementary restriction brings us even further away from the intuitive vision of space and time as used in classical science.

Internal Time

Let us now outline the direction in which we see the solution to the problem of irreversibility. An unexpected development of modern dynamic systems theory is the importance of unstable systems, in which arbitrary small differences in initial conditions are amplified (see fig. 3). Whatever the size of the initial region A, there are trajectories which lead to regions A_1 or A_2. Since each region contains diverging types of trajectories, we can no longer perform in a meaningful way the transition from finite measure ensembles in phase space (such as region A in fig. 3) to individual points corresponding to trajectories. Sufficiently strong instability of motion leads to the loss of the concept of a trajectory as a physically meaningful concept. This is a fundamental fact that makes possible the incorporation of probability and irreversibility in physical theory without invoking the idea of ignorance.

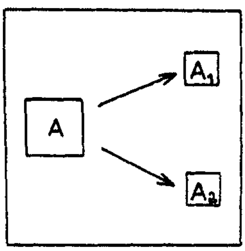

FIG. 3.—Unstable dynamical systems: whatever the age of region A, this region is split, time going on, into regions A_1 and A_2.

A simple example of an unstable dynamical system is provided by the so-called baker transformation (see fig. 4). It may be seen as the transformation B of the unit square onto itself which is the result of two successive operations: first, the unit square is squeezed in the vertical direction to half its width and is at the same time elongated in horizontal directions to double the length; next, the resulting rectangle is cut in the middle and the right half is stacked on the left half. The iterations B^n of B may be considered to model the dynamical evolution of a system at unit intervals of time.

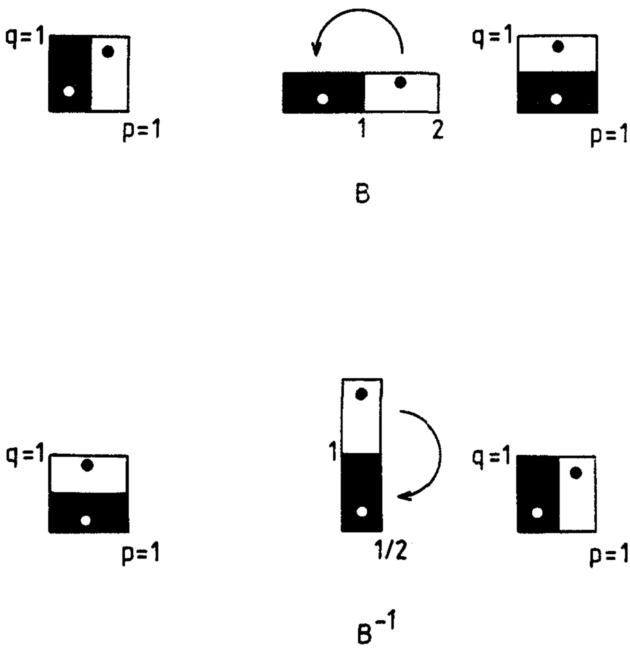

FIG. 4.—An illustration of the baker transformation B and its inverse B^{-1}. The path of the two spots gives an idea of the transformation.

A basic feature of highly unstable systems, which was recognized by B. Misra, is that we may introduce for such systems a new concept, that of "internal time" or "internal age" (Misra and Prigogine 1983a; Prigogine and Courbage 1983; Misra, Prigogine, and Courbage 1979; Misra and Prigogine 1983b). Internal time is quite different from the usual parameter time, which I can read on my watch. For example, it corresponds more closely to the question I ask myself when I meet a stranger and wonder how old he is. Obviously the answer will depend on his overall appearance: age cannot be read from the color of the hair or the wrinkles on the skin alone; it depends on the global impression of the person. As a second example, internal time comes closer to ideas recently put forward by geographers, who have introduced the concept of chronogeography (Parks and Thrift 1980; Carlstein, Parks and Thrift, eds. 1978). When we look at the structure of a town or a landscape, we see temporal elements interacting and coexisting. Brasilia or Pompeii would be examples of cities having well-defined internal age. On the other hand, modern Rome, whose buildings originated in quite different periods, would be an example of having an average internal time.

For simple unstable systems, such as those corresponding to the baker transformation, we may reach a more quantitative understanding of internal time. Let X_o be the function which assumes the value -1 on the left half of the square and $+1$ on the right half. Let us define $X_n = U^n X_o$ corresponding to the application of n baker transformations. A few of these iterations are represented in figure 5.

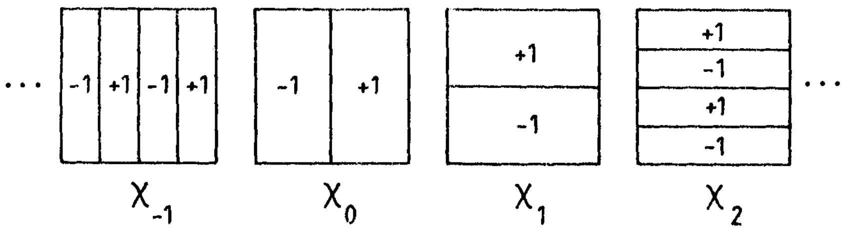

FIG. 5.—Partitions generated from χ_0 through successive applications of the baker transformation.

The various functions X_n are eigenfunctions of internal time. The internal time is necessarily an operator like the ones we use in quantum mechanics. Arbitrary partitions of the square do not have a well-defined internal time but only an average internal time. In contrast, the partitions represented in figure 5 correspond to well-defined internal times starting with 0 for partition X_o. The age of the partition X_n is the number n of iterations I have to perform to go from X_o to X_n. Whenever internal time exists, it is an *operator* and not a number. It is important to grasp this difference: an arbitrary partition of the square has no well-defined internal time (as has the partition X_n); in general, we then can only speak of an average internal time.

Instead of using the baker transformation to illustrate these ideas, we could use a glass of water into which we pour a drop of ink. The internal time is now related to the shape the ink takes, but an arbitrary distribution of ink in water has no well-defined internal time, because several ink drops may have been introduced at various times.

The existence of an internal time operator has some far-reaching consequences. We now are able to describe the evolution of the system no more in terms of trajectories but instead in terms of partitions.

Obviously, these two types of description, one in terms of partitions and the other in terms of trajectories, are complementary in the sense used in quantum mechanics (to describe however a physically quite different situation). If the state is described by a partition, we know only that the system is in a region of phase space (for example, in a region corresponding to the numerical value +1 in fig. 5); but we do not know its exact location. Similarly, a point in phase space may be embedded in an infinite number of partitions. The internal age of a trajectory is undefined.

In more technical terms, the dynamics of unstable systems equipped with internal time corresponds to an algebra of noncommuting observables. Once we use internal time and partitions, we have lost the local point of view of classical mechanics. Instability leads to *nonlocality*. In this way, the main obstacle for the transition between dynamic theories and probabilistic description is eliminated. Als long as the basic description used in classical mechanics was the trajectory, there was no hope to reach a microscopic theory of irreversible processes. However, for highly unstable dynamical systems we have an alternative way, which involves a topological description and eliminates the appeal to trajectories.

It is only for these systems that the second law of thermodynamics may be meaningful in an intrinsic sense, and not be the mere outcome of approximations or errors. These systems are of tremendous importance, as they encompass all chemical systems and therefore, also, all biological ones.

Open Future

We have now reached the core of the problem: What is time? According to Rudolf Carnap:

> Once Einstein said that the problem of the Now worried him seriously. He explained that the experience of the Now means something special for man, something essentially different from the past and the future, but that this important difference does not and cannot occur within physics. That this experience cannot be grasped by science seemed to him a matter of painful but inevitable resignation. I remarked that all that occurs objectively can be described in science: on the one hand the temporal sequence of events is described in physics; and, on the other hand, the peculiarities of man's experiences with respect to time, including his different attitude toward past, present and future, can be described and (in principle) explained in psychology. But Einstein thought that scientific descriptions cannot possibly satisfy our human needs; that there is something essential about the Now which is just outside of the realm of science (Schlipp, ed. 1963).

As I mentioned earlier, we begin to see a way out of the difficulty that plagued Einstein. But the concept of time which may incorporate the

"Now" in a more fundamental sense is indeed quite different from the traditional, linear representation as it came to us from Aristotle.

We could in fact imagine a world in which we would not age all together: the future of some would be the past of others. However, this is not our world. As we have seen for unstable dynamical systems, for which we can define the internal time, a different description becomes available. For example, consider a distribution in phase space as represented in figure 6. We can represent this distribution as a superposition of the basic partitions as introduced in figure 5. In mathematical terms, this corresponds to the formula

$$\rho = \sum_{n=-\infty}^{n=+\infty} c_n X_n \qquad (2)$$

The index $n = 0$ corresponds to the present; the values $n > 0$ correspond to the future, while the values $n < 0$ correspond to the past. The important point is to notice that Σ extends symmetrically over the past and the future. X_n is the partition corresponding to internal time n. This confronts us with a quite interesting situation: while the classical distribution of past, present, and future refers to a given, astronomical time (time as read on a watch), the new description combines, as expressed in formula (2), contributions coming from all values of the internal time. In this sense time becomes nonlocal: present is a recapitulation of the past and an anticipation of the future.

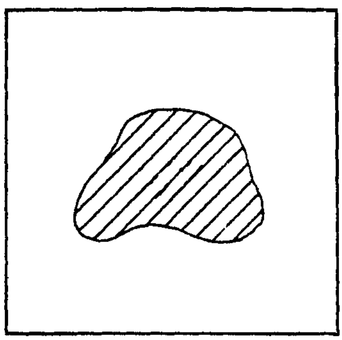

FIG. 6.—Arbitrary distribution in phase space, which can be written as a superposition of partitions as represented in figure 5.

A comparison with our own situation may help. The present state of our neuronal system contains an essential element of our past experience and an element of anticipation of future events. However, for time as it is implied, for example, in the neurophysiological activity, future and past cannot appear as symmetrical.

We may now introduce this asymmetry or, equivalently, the second law in our description. Basically, this corresponds to giving a different weight to the past and to the future. Instead of the distribution function ρ we now introduce an appropriate transform of ρ, which we shall call $\tilde{\rho}$ and which can be shown to satisfy a probabilistic evolution equation and reach equilibrium for the distant future:

$$\tilde{\rho} = \Lambda \, \rho \tag{3}$$

where Λ may be constructed when the internal time T is known. In fact, it is a decreasing function of the internal time. Instead of formula (2), we may now write

$$\tilde{\rho} = \sum_{-\infty}^{+\infty} c_n \, (\lambda_n \, X_n) \tag{4}$$

Again, the Σ extends from $-\infty$ (the far-distant past) to $+\infty$ (the far-distant future). But there is an essential difference with equation (2). The contribution X_n corresponding to internal time n is multiplied by a number λ_n (the value of Λ for $T = n$). The numbers λ_n are positive, and form a decreasing sequence:

$$\lambda_n \rightarrow 0 \qquad \text{For } n \rightarrow +\infty$$

This has an important implication: future is open from the point of view of internal time. Indeed, the contributions coming from n positive and large are damped by the multiplication with λ_n. In other words, future is not contained in the present for systems satisfying the second law of thermodynamics. Therefore, according to this description, states have an orientation in time. Time is now intrinsic to objects; it is no more a container for static, passive matter.

I find it quite striking that the closest links with the conclusions we have reached are to be found in the work of two poets. One is Paul Valéry; let me quote one of the remarks we find in the *Cahiers*:

> —En somme, je *crois* qu'il y a une mécanique mentale qu'il ne serait pas impossible de préciser.
>
> Mais cette mécanique, qui doit s'inspirer de l'autre toutefois ne doit pas craindre de prendre ses libertés nécessaires—c'est-à-dire de contredire la première sur les points qu'il faut.
>
> Ainsi la variable temps est profondément différente. Le temps mental est plus une fonction qu'une variable, en psychologie—et on trouvera $\frac{\delta t}{\delta F}$ plus souvent que $\frac{\delta F}{\delta t}$ (Valéry 1973, 1:1303).[1]

This is a most vivid evocation of the topological time we have been describing in this essay. The other is T. S. Eliot. You know these verses from "Burnt Norton":

> Time present and time past
> Are both perhaps present in our future
> And time future contained in time past

It would be difficult to express in a clearer way the connection which exists between past, present, and future. But Eliot continues:

> If all time is eternally present
> All time is unredeemable (Eliot 1968).

Indeed time would be unredeemable in a deterministic world, however, in a universe submitted to the second law, whose microscopic foundations imply instability and therefore a stochastic description of time evolution, time is redeemable. As a result, we begin to understand the difference between the tautological universe, which has obsessed us since the dawn of physical thought, and the reality of time we experience in the world into which we have been thrown.

Philosophical Perspectives

We have been led to the conclusion that broken time-symmetry is an essential element in our understanding of nature. A simple musical experiment may illustrate what we mean by this statement. We may play a sound sequence during a given time-interval, say one second, starting for example with *piano* and ending with *fortissimo*. We may play the same sequence in reverse order. Obviously, the acoustical impression is deeply different.

This can only mean that we, equipped with an internal arrow of time, distinguish between these two performances. In the perspective we have summarized in this essay, this arrow of time does not oppose man against nature. Far from that, it stresses the embedding of mankind in the evolutionary universe which we discover at all levels of description. Time is not only an essential ingredient of our internal experience and the key to understanding human history, both at the individual and at the social level. It is also the key to our understanding of nature.

Science, in the modern sense, is now three centuries old. We may distinguish two instances when science has led us to a well-defined image of the nature of physical existence. The first was that of Newton with his world view formed by changeless substances and states of motion, with a conception in which matter was dissociated from space and time because time and space appeared as passive containers of matter. The second was reached by Einstein. Perhaps the greatest achievement of general relativity is that space-time is no more independent of matter but is itself generated from matter. Still, in Einstein's view, it was essential to keep the idea of localization in space-time as an integral part of the theory.

We now begin to reach a third instance in which this localization in space-time is submitted to a more thorough analysis. Curiously, this questioning of the microscopic structure of space-time emerges at present from two quite independent directions: quantum theory and the microscopic theory of irreversibility. Our relation with nature, and especially the fact of our constant learning about nature, become only meaningful in this perspective, which incorporates instability and irreversibility. What could be the meaning of learning if tomorrow would always be given today?

It is remarkable to see how close these third stage conclusions are to the anticipations of Whitehead and Heidegger. In his basic work *Process and Reality* (1929), Whitehead emphasizes that simple location in space-time cannot be sufficient, that the embedding of matter in a stream of influence is essential. Whitehead emphasizes that no entities, no states can be defined without activity. No passive matter can lead to a creative universe. The title of Heidegger's influential book *Being and Time* (1927) is in itself a manifesto, emphasizing Heidegger's opposition to the timeless concept of Being, which corresponds to the main stream of western philosophy since Plato.

States may be associated with Being, and time evolution with Becoming. States as defined by formula (2) are time-symmetrical (in reference to internal time). This is the basic relation between Being and Becoming, as often described in Western physics. Being is independent of time. But this description does not include the second law of thermodynamics. Once this is included, we come to relations (2) and (3) with a broken time-symmetry, which is then propagated by time-symmetry broken laws of evolution, including the second law of thermodynamics. From a logical point of view there are therefore two possible solutions to the problem of Being and Becoming. However, our existential situation allows us only to retain the solution involving a broken time symmetry.

Two centuries ago Kant asked three questions: What can I know? What should I do? What may I hope? He thought that only speculative philosophy could give contributions to the answers. I believe today the situation appears quite different. Science also can make a contribution to the basic interrogations of humanity. For example, we have overcome the basic duality between humanity and the universe, in which time was the main element in the opposition.

It seems to me that we are living in a most exciting moment of the history of science. We have slowly come to a description of time which, in addition to its traditional distinctive features, incorporates new characteristics such as irreversibility, evolution, and creativity. This century has already known two great revolutions in basic theoretical physics. Whatever the detailed methods will be, it seems clear to me that we are approaching a point where the rediscovery of time will lead not only to a better understanding of the mechanisms of change, which we encounter at all levels of the universe we observe, but also to a better embedding of human beings in the universe from which we have emerged. As beautifully summarized by G. Steiner in his comment on Heidegger, "the human person and self-consciousness are not the center, the assessors of existence. Man is only a privileged listener and respondent to existence" (Steiner 1982). The new description of time thus puts in a new perspective the question of the value of science for ethics. This question could have no meaning in a world viewed as an automaton. It acquires a meaning in a vision in which time is a construction, a construction in which we all participate.

NOTE

1. "In short, I *believe* that there is a mental mechanics that would not be impossible to clarify.

"But this mechanics, which must be inspired by the other one, however must not fear to take the necessary liberties—that is to say of contradicting the first on all the necessary points.

"Thus, the time variable is profoundly different. Mental time is more a function than a variable in psychology—and one will find $\frac{\delta t}{\delta F}$ more often than $\frac{\delta F}{\delta t}$."

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