THE REDISCOVERY OF TIME

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Introduction ...

In the preface to the 1959 edition of *The Logic of Scientific Discovery*, Sir 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."

It is obvious that the meaning of time plays an important role in the problem so beautifully spelled out by Sir Karl 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.

Till 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 processes that involve an "arrow of time". If you 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 of chemistry also 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, science and the humanities.

Most of European modern philosophy, from Kant to 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 perspective I could only confirm the views expressed by Ivor Leclerc:

"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."

However, I believe that the situation today is much more favorable in the sense that the recent rediscovery of time leads to a new perspective. Now the dialogue between hard sciences on one side, human sciences and philosophy on the other, may become again fruitful as it was during the classic period of Greece or during the 17th century of Newton and Leibniz.

To illustrate this coming together on a fundamental point, let us consider in this lecture the relation between Being and Time, to take up the title of the influential essay of Martin Heidegger.

Of Being and Becoming

This relation may probably be considered as one of the central themes of Western philosophy. The aim of my lecture 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. I do not feel prepared to discuss the theological context; however, I believe that such a discussion will always encompass the new concepts science affords us about man's position in nature, and is therefore unavoidably related to a discussion of the problem of Being and Time, or Being and Becoming.

Let us start with a brief summary of the way in which time was described in classical Physics. Western scientific tradition takes for granted since Aristotle 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.

This description is used in classical physics, as well as with minor modifications, in quantum theory and in relativity. While immensely useful, it does not do justice to the various connotations of time. Past seems to disappear in the present. Present disappears in the future. No intrinsic connection appears between past, present 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 age all together?

We have therefore to reconsider the meaning of time. This, as is well known, was the conclusion reached by Bergson, Whitehead, Husserl and Heidegger, to quote only some of the deepest thinkers of our days. However, in contrast with their approach, I want to show here that a new time concept can be generated from within modern science, and does not imply a complete break with the scientific tradition of the West.

The Problem of Irreversibility

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

The difficulties in the understanding of irreversibility show up very clearly in the classical approach of Boltzmann. Let us consider the entropy S, which is 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**.

Here, k is a universal constant, the so-called Boltzmann's 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.

I have no intention of going into the controversies to which it has led, but 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 w0, to a region E in phase space:

Diagram to be inserted here

Suppose our basic description were in terms of trajectories, as is the case in classical mechanics. Then the transition probability would be one (I) if the domain E would contain the trajectory at point t, and would vanish otherwise. In a genuine probability theory, this is not so. Then, the numbers associated with transition probabilities are positive numbers comprised between o and I. How is this possible? We come immediately to a dilemma. One possibility is to refer to our ignorance: we don't know which trajectory to consider. 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.

It is difficult, however, to reconcile this interpretation with the constructive role of irreversibility. We know today that irreversibility is at the root of self-organisation in chemistry and physics, and plays a central role in biological processes. Therefore, life cannot be the outcome of our own errors, 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 understands that great scientists such as Einstein have been reluctant to take it.

However, the conflict between fundamental dynamic theories, be it classical dynamics, quantum mechanics or relativity and the second law of thermodynamics, is unavoidable.

The Nature of a System's History

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 for 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. He summarises 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. It is true that we are embedded in an expanding universe. However, the second law of thermodynamics is not universal. We may imagine dynamic systems such as the undamped harmonic oscillator or the two-body planetary motion to which we cannot apply the second law.

Still 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 transmit signals. Similarly 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 is greater than o) for the quantum world are as strange as the implications of the finiteness of the speed of light (c is less than infinity) for space and time in relativity theory. Both lead to realities beyond our common experience that cannot be rejected."*

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. The second law has therefore to 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.

Resolution of the Problem of Irreversibility

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. Arbitrary small differences in initial conditions are amplified. The situation is represented schematically below:

Diagram to be inserted

Unstable dynamical systems:
whatever the age of region A,
this region is split, time going on,
into regions AI and A2.

Whatever the size of the initial region A, there are trajectories which lead to regions AI or A2. As each region contains diverging types of trajectories we can no more in a meaningful way perform the transition from finite measure ensembles in phase space (such as region A) to individual points corresponding to trajectories.

Sufficiently strong instability of motion leads to the loss of the concept of a trajectory as a physical meaningful concept. This is a fundamental fact which makes possible the incorporation of probability and irreversibility in physical theory without invoking the idea of ignorance.

A simple example of an unstable dynamic system is provided by the so-called baker transformation which we shall use again later as an example. It may be seen as the transformation B of the unit square onto itself which is the result of two successive operations: (I) 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; (2) next, the resulting rectangle is cut in the middle and the right half is stacked on the left half. The iterates of B may be considered to model the dynamic evolution of a system at unit interval of time.

Diagram of baker transformation to be inserted.

A basic feature of highly unstable systems, which was recognised by B. Misra, is that we may introduce for such systems a new concept, corresponding to the "internal time" or "internal age." Internal time is quite different from the usual parameter time, which I can read on my watch.

It corresponds more closely to the question which I ask when I meet a stranger and I wonder how old he is. Obviously the answer will depend on the overall appearance. His age cannot be read from the colour of the hair, the wrinkles on the skin. It depends on the global aspect. Internal time comes closer to ideas recently put forward by geographers, who have introduced the concept of "chronogeography".

When we look at the structure of a town, or of a landscape, we see temporal elements interacting and coexisting. Brasilia or Pompeii would correspond to a well-defined internal age. On the contrary, modern Rome, whose buildings originated in quite different periods, would correspond to an *average* internal time.

For simple unstable systems such as those corresponding to the baker transformation, illustrated above, we may reach a more quantitative understanding of internal time.

Let XO be the function which assumes the value-I on the left half of the square and + I on the right half. Let us define Xn = Un XO corresponding to the application of n baker transformations. A few of these iterations are represented below:

Generations of Partitions through
successive applications of the baker transformation.
Schematic to be inserted.

The various functions Xn are "eigenfunctions" of internal time. The internal time is necessarily an *operator* like the one 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 on the illustration just provided correspond to well defined internal times starting with o for partition Xo. The age of the partition Xn is the number n of iterations I have to perform to go from Xo to Xn.

Whenever the 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 Xn). In general, we 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, as the ink may have been introduced at various times.

On the Existence of *Internal* Time

The existence of an internal time operator has some far-reaching consequences. We now are able to describe the evolution of the system in terms no more of trajectories, but of partitions. Obviously, these two descriptions, one in terms of partitions, 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; but we don't 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 non-locality. In this way, the main obstacle for the transition between dynamic theories and probabilistic description is eliminated. As long as the basic description used in classical mechanics was the trajectory, there was no hope to reach a microscopic theory of irreversible processes. But for highly unstable dynamic 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 of chemical systems, and therefore also all of biological ones.

We have now reached the core of the problem: What is time? According to 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 seems 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.*

As I mentioned earlier, we begin to see a way out of the difficulty which 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. This is, however, not our world. As we have seen for unstable dynamic systems, for which we can define the internal time, a different description becomes available. As an example, consider a distribution in phase space as represented in the illustration to be found on the following page. We can describe this distribution (Y) as a superposition of the basic partitions introduced in the illustration above.

Schematic to be inserted.

In mathematical terms, this corresponds to the formula:

Y = SUM (from n = + infinity, to n = - infinity) Cn Xn ... (Equation I to be inserted)

The index n = o corresponds to the present; the values "n is greater than o" correspond to the future, while the values "n is less than o" correspond to the past. The important point is to notice that SUM extends symmetrically over the past and the future. Xn 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, as expressed in the mathematical formula just given, combines contributions coming from all values of the internal time. In this sense, time becomes "non-local" - the present is a recapitulation of the past, and an anticipation of the future.

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 neuro-physiological activity, present 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, as the following formulas and equations will show:

Instead of the distribution function t we now introduce an appropriate transform of t which we shall call t* and which can be shown to satisfy a probabilistic evolution equation, and reach equilibrium for the distant future:

t* = A t ... (Equation 2)

In this formula, A may be constructed when the internal time T is known. In fact, it is a decreasing function of the internal time. Instead of (Equation I), we may now write:

t* = SUM (from + infinity to - infinity) Cn (An Xn) ... (Equation 3)

Again, the SUM: extends from minus infinity (the far distant past) to plus infinity (the far-distant future). But there is an essential difference with (Equation I). The contribution Xn corresponding to internal time n is multipled by a number An (the value of A for T = n).

The numbers An are positive, and form a decreasing sequence, as (Equation 4) will show:

An ~~-> 0 For n ~~-> + infinity ... (Equation 4)

This has an important meaning: 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 An.

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 of static, passive matter.

On the expression of poets

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 Valery; let me quote one of the remarks we find in the *Cahiers*:

-En somme, je crois qu'il y a une mecanique
mentale qu 'il ne serait pas impossible de preciser.
Mais cette mecanique, qui doit s'inspirer de l'autre
toutefois ne doit pas craindre de prendre ses libertes
necessaires-c'est-a-dire de contredire la premiere
sur les points qu'il faut.

Ainsi la varible temps est profondement differente.
Le temps mental est plus une fonction qu'une variable,
en psychologie-et on trouvera plus souvent que.

This is a most vivid evocation of the topological time we have been describing in this lecture.

The other is T. S. Eliot. You know these verses from *"Burnt Norton":*

Time present and time past
Are both perhaps present in time 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.

Indeed, time would be unredeemable in a deterministic universe. But 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 in which we have been thrown.

Time and the History of Science

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 which we have summarised in this lecture, this arrow of time does not oppose man with 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 the understanding of 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 moments where science has led us to a well-defined image of the nature of physical existence:

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- One was the moment of Newton, with his world view formed by changeless substances and states of motion, with a conception in which matter, space and time were dissociated as time and space appeared as passive containers of matter.
- A second state was reached by Einstein. Perhaps the greatest achievement of general relativity is that space-time is no more independent of matter. It is itself generated from matter. Still, in Einstein's view, it was essential to keep the idea of localisation in space-time as an integral part of the theory.

We now begin to reach a third stage, in which this localisation 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 problem of learning and measuring, become only meaningful in this perspective, which incorporates instability and irreversibility.

It is remarkable to see how close some recent conclusions are to the anticipations of Whitehead and Heidegger. In his basic work *Process and Reality*, Whitehead emphasises that simple location in space-time cannot be sufficient that the embedding of matter in a stream of influence is essential. Whitehead emphasises 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* is in itself a manifesto, emphasising Heidegger's opposition to the timeless concept of Being, which corresponds to the mainstream of western philosophy since Plato.

States may be associated with Being, and time evolution with Becoming. States as defined by Equation I are time symmetrical (in reference to internal time).

We now have an example of the 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 done, we come to relations expressed in Equations I and 2 with a broken time-symmetry, which is then propagated by time-symmetry broken laws of evolution, including the second law of thermodynamics.

Prom a logical point of view, there are therefore at least four 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.

Science and Philosophy - Conclusions and Becomings ...

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 as quite different. Science can also give a contribution to the basic interrogations of mankind.

We have overcome the basic duality between man and the universe:
Time was the main element in the opposition between man and the universe.

It seems to me that we are living in a most exciting moment of the history of science. We slowly come to a description of time which, in addition to its traditional distinctive features, incorporates some of its main connotations, 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 approach a point where the rediscovery of time will lead not only to a better understanding of the mechanisms of change, which we encounter on all levels of the universe we observe, but also to a better embedding of man in the universe from which he has emerged.

As beautifully summarised 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."

The new description of time puts in a new perspective the question of the ethical value of science. 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 in which we all participate.

Ilya Prigogine
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