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About Time

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Physicists share a general consensus on the formal treatment of time within their theories, which does not preclude, however, the possibility of differences in understanding and interpretation, as shown on several examples, taken mainly from the so-called 'special' and 'general' theories of relativity. The historical roots of the pitiful neglect of this conceptual variability are sketched. We are finally led to wonder about the possibility of alternative theorizations of time in physics.

> *"For the times, they are a-changing"*
> Bob Dylan

Questioning time is as old as philosophy. Modern science, mainly physics, has taken up the challenge and subjects the public to a steady flow of essays on its present views. Is it justified, though, for physicists, to believe and make believe that science offers firm and final answers to the questions it is asked or asks itself, especially when dealing with such a major theme, which should not be unduly monopolized? Let me offer, then, a few variations, sometimes dissonant, on this theme.

SHOULD PHYSICISTS BE BELIEVED?

A large majority of physicists today agree on the general framework of their investigations, whether it be in cosmology, particle physics, or statistical mechanics. This agreement, however, might be deceptive. It essentially concerns the theoretical machinery, that is, the mathematical formalisms used to account for our experience of the world, and the computational procedures

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which enable us to derive from these formalisms explanations or predictions about our observations—in short, what may be called ‘the equations.’ But such a consensus leaves unresolved all questions bearing on the interpretations of these theories and the significance of the concepts they rely on—in short, ‘the ideas.’ Behind the facade unity of the scientific community, one may find serious intellectual divergences, all the more deeper since they are rarely made explicit. The agreement on formalisms does not extend to the notions they are supposed to convey, nor to the language used to express them. This multiplicity of conceptions, though, often is masked by the indifference or prudence shown by most scientists outside the field of their highly specialized work. It must then be stressed with some insistence that the formal unity of physics may be compatible with a large conceptual diversity—and fortunately so, since it would certainly be damaging for science if it could not propose the variety of perspectives which is the wealth of any endeavor worthy of the beautiful name of culture. Thus, even if scientists are right, one is not forced to believe them, or, at least, to take their word(s) . . .

Considering time, here are a few examples of current statements, to be found in most textbooks or popular articles, the adequacy of which may be legitimately discussed, without questioning the validity of the theories they are supposed to express:

- It is commonly said that Einsteinian relativity has brought the unification of space and time within a common substrate, space-time. But the classical conception of space and time, the theory which underlies Galilean and Newtonian mechanics, already mixes up, and deeply so, time and space. Indeed, the spatial distance between two events need not be the same in two equivalent reference frames, and depends on the elapsed time; the start and end of the fall of a spoon dropped by a waiter in a dining-car, while they take place on the same vertical line for the client in the train, are horizontally far apart for the cow which contemplates the train passing by. Of course, if Galileo and Newton blend time with space, Einstein goes much further and blends as well space with time, which certainly opens new and revolutionary vistas; nonetheless, the very idea of relativity goes back to Galileo, even though Einstein introduced a radical change in the specific expression of the relativity principle. It is easy to exhibit numerous examples showing that, if Einsteinian relativity still is poorly understood, it is often because its predecessor, Galilean relativity, is not fully mastered yet [1] (see ref. 2 for a technical review). As an example of such misunderstandings within the realm of quantum theory, consider the common but mistaken opinion which relates the notion of spin to Einsteinian relativity, although it is already predicted by a consistent use of Galilean relativity [3].

- To stay with Einstein, the theory of gravitation he built, commonly and awkwardly called 'general relativity,' is considered as a pure geometry of space-time, supposedly 'curved' by matter. While this geometrical interpretation has a noble historical priority and an undeniable aesthetic value, it nevertheless constitutes a very particular point of view, which shows at least one serious inconvenience, namely, that of radically separating gravitation from the other interactions (electromagnetic, nuclear, etc.). These are essentialy dealt with by dynamical and nongeometric theories, where the esssential notion is that of a 'field,' as the physical mediator of interactions. Now, it is perfectly possible to reintegrate gravitation within this general framework and to build its theory with a (tensor) field in flat space-time as mediator. The universal coupling of the gravitational field with energy, that is, in particular with its own, then induces an essential nonlinearity which leads precisely to the usual Einstein equations. The last step is to understand that the very same universal coupling will endow the tensor field of gravitation with the role of an effective (variable) metric masking the underlying flat one. One recovers the exact expression and predictions of the conventional theory, although with a deeply different epistemological contents.[2]
- Modern cosmology, as expressed by the so-called 'big bang' theory, exhibits a starting point in time—I stay here with classical cosmology and do not consider its quantum developments. This is the supposed 'beginning of the universe,' some 10–20 billion years ago, a notion which leads to serious conceptual problems, and lends itself to many esoteric or religious interpretations. Now, the strictly theoretical formulation, which is largely consensual, is much more technical and less glamorous: one speaks of 'an essential initial singularity on the time axis,' which is a well-defined and nontrivial mathematical notion. To translate this statement in lay terms as a 'birth' or 'creation' of the universe goes well beyond its scientific meaning. Moreover, a correct understanding of the formal expression in fact undermines the popular interpretations in term of a 'beginning.' For a singularity, precisely, does not belong to the range of the physically admissible values, and does not characterize, properly speaking, an instant. It is then quite natural, and very easy, to introduce, without arbitrariness, a new temporal parametrization in which the singularity recedes to minus infinity, dissipating any notion of an initial instant. It thus becomes possible to state simultaneously and consistently that the universe is some 20 billion years old (on a certain conventional calendar) *and* that it has always existed [5].
- A more anecdotical case, but an amusing one, is that of the statement, which by now has become a 'cliché' to be found in popular books as well as in introductory textbooks, according to which "nothing can go faster than

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[2] See ref. 4 for a more detailed presentation of the argument with numerous original references.

light." Taken at face value, this is simply wrong, as shown by an elementary and well-known (but only to those who know it) example. Imagine a lighthouse, the beam of which accomplishes, say, one turn per second, and projects a light spot on a circular wall centered on the lighthouse; the spot clearly runs around the circumference of the wall in 1 sec as well, whatever the circumference. Let the radius of the wall be, say, 100,000 km. The spot then will cover something like 600,000 km in 1 sec, that is, will have a speed twice as high as the velocity of light: light itself going faster than light? Of course not, since the spot is not 'made of' light, and is but an appearance formed by the successive impact of the rotating beam, within which light indeed travels with its own velocity (as with the water jet from a rotating sprinkler, the beam is curved, but each drop or photon goes straight ahead). Nonetheless, the phenomenon (the spot certainly deserves this name) does exhibit a real faster-than-light displacement, which, by the way, is quite observable—think of the laser beams commonly shot at the Moon (or, using electrons instead of photons, of very fast oscillographs). Neither matter, nor information, though, if one considers carefully the problem, is involved in this ultraluminous motion, so that it does not shake a single piece of Einsteinian relativity—provided its statements are phrased with sufficient care (for instance: "neither energy nor information can travel faster than light"—which is not the same as 'nothing'). That such considerations are not completely trivial is shown by the bewilderment of most people, including physicists, when first subjected to this (pseudo)paradox. Note also that no physical *causes* can go faster than light, but *correlations* may—which leads to interesting thought-experiments, reminiscent of (although not at all equivalent to) quantum correlations.

Such situations (and many other ones: the above selection is but a very partial one, dealing specifically with the theme of time) are rarely confronted in the usual practice of physics, as their elucidation is not necessary for the correct functioning of its theoretical machinery. The fearful efficiency of its formalism constitutes the strength of physics; its concepts need not be understood to be put at work, and one may be a great physicist and a poor epistemologist. But here lies as well the weakness of our science; if its common work (at least in its 'normal' phases, to use Kuhn's categorization) does not suffer from such ignored ambiguities, they surge with the violence of the repressed in critical moments ('revolutionary' phases), and, more often, when science comes out of its ivory tower to confront the lay world, in teaching, popularizing, or philosophizing. It cannot be but a provisional strategy, and one which implies a serious loss of substance, to look away from the inescapable and fecund multiplicity of meaning within science, lurking behind its apparently unified and pacified orthodoxies.

TIME *OF* AND *IN* PHYSICS

One of the reasons for this accepted self-mutilation of present science is that physics certainly inquires about time, but very little upon *its* time, the time of its own evolution, its history. This very amnesia results in a permanent confusion, when asserting our knowledge, between a chronological (one does not dare to say 'historical') account and an epistemic attitude [6]. Scientific discovery is a contingent endeavor, and its successive stages have no reason to be linked by a logical chain; erroneous conceptions and improper terms necessarily mark out the real path leading to any scientific achievement. Permanent critical care is thus needed in order to sort out the most pernicious of these words and most confused of these conceptions. The above examples could be considered anew in this perspective.

But it is not only the history of physics as such and of its specific notions that we should take into account when trying to assess its validity and relevance. In the case of time more than for any other notion, we need to consider a wider context. In particular, greater attention is to be devoted to the relationship between scientific theories and technological practices. Our ideas on time cannot be separated from the way we measure it; the evolution of these ideas, from Galileo to Hawking, through Newton and Einstein, is intimately linked to the progress of instrumentation, from the primitive mechanical clocks of the Renaissance to the sophisticated atomic clocks of today. The point is not only to stress the instrumental role of the experimental procedures, but to recognize as well their conceptual significance. Namely, any reflection on the concrete measuring of time leads, in a much more direct and constraining way than an abstract analysis, to the inescapable and delicate dialectics of linear versus cyclical time; time has no meaning without change, but the very measuring of time requires a repetition with no change. To mark the passing of time within some process of change, there must exist some stable 'unit of time,' repeating itself identically. But such a constancy has to be assumed and cannot be proved *a priori*, since it would require comparison with an already established measure of time; one must first postulate the identity of the durations of the successive revolutions of the Earth along its orbit, or of the hands of a watch, before (and for) being able to check, refine, or replace these hypotheses. Here lies probably, in this confrontation between transformation and repetition, the tightest epistemic knot of the notion of time.

Another example, already alluded to, eloquently shows how conceptual problems, "epistemological obstacles" (Bachelard), and pedagogical difficulties, if one is to face them with some chance of success, require fully taking into account the historical dimension and the cultural context. Analyzing the considerable shock exerted at the beginning of the century by the appearance of Einsteinian relativity on lay people as well as on experts, one cannot but conclude that a large part of the upheaval was due to the late effects of the Galilean revolution rather than to its Einsteinian reform. Only the historical conditions of the nascent century, and in particular, the cultural atmosphere of the immediate postwar period, explain the public divulging of an open secret: physicists had dared to touch upon the fabric of space and time, so that the very framework of our existence seemed to have been shaken. But by the time in 1919 when Einstein and his relativity reached the front pages of popular journals, the scandal, for the essential, had been perpetrated for three centuries. One cannot hope to dissipate such confusions if one does not take due account of their nature and origin.

One should probably not be too much surprised that the underestimation of the width, weight, and complexity of historical time and its effects is so deep and common with physicists, as they have been spoiled for four centuries by a particularly simple, not to say simplistic, conception of time, with a remarkable efficiency—perhaps even an 'unreasonable' one, to echo Wigner's words on the efficiency of mathematics in general. For Newtonian time (and Einsteinian time as well) is an idealization, consisting of a homogeneous and continuous 'stuff,' while being as well composed of autonomous (infinitesimal) instants, each one being in immediate relationship with its immediate predecessor and successor. Continuity here is limited to contiguity, and the conceptual difficulty of such a purely local notion of temporal coherence is cleverly overcome by the technique, nowadays routine despite its persisting intellectual challenge, of the infinitesimal calculus. In this framework, the evolution of mechanical systems, too rapidly considered as an archetype of the objects populating the world, is such that their future is entirely determined by their present (even though one has to recognize—at long last—that this evolution often cannot be predicted because of sensitivity to initial conditions). In other words, mechanical systems have no 'memory.' But human time, whether it be that of individuals or of societies, does not follow such a rudimentary scheme, and future evolution largely depends on the whole of past history, which cannot be summarized in the only knowledge of the present state (not to speak of the fact that the future also depends upon itself, via the human ability of anticipating). Physicists have some difficulty in grasping and working out such a situation, as they are accustomed to differential equations, essentially local in time, which still are the dominant paradigm in their conception of time evolution (note that 'hereditary system,' governed by integrodifferential equations, which could offer alternative models, do not belong to the usual toolbox of physicists).

NEW TIMES AHEAD?

Perhaps our questioning should be pushed backward, up to the very sources of the formalization of time by theoretical physics. The Newtonian paradigm of a *linear, uniform, continuous, reversible* time has met with an undisputed success. But this very success should not hide the fact that this is, after all (or before all?), a modelization, a theoretical construct, abstracted from our common and complex experience. Its simplicity, which makes its strength, might lead to oversimplification. This physicists' time, rather than an objective time, is an objectified one, which should not be reified. For the risk becomes great to believe that time *is* this linear axis drawn upon a sheet of paper in so many graphs. Indeed, our intuitive notion of time notoriously is much richer than the abstraction extracted from it by theoretical physics. Time as we live it is not uniform, nor reversible; dyssymetry between past and future certainly is one of its primary characteristics. This time—ours—cannot be analyzed as a succession of pointlike instants; its stuff is much fuzzier: our present is not a single point without extension on an abstract axis, but a small temporal zone (a few milliseconds?), 'sliding' along with the course of time. The separation between past and future is not a discontinuous cut, a dimensionless present deprived of width, but a continuous transition through which future progressively changes into past; present is that very process. And time not only has 'width,' it also shows 'thickness'; rather than by a thin string, it would better be described by a threaded rope. We do live simultaneously several intertwined temporalities, different in their nature (the time of our sensations, that of our ideas, that of our social relationships, etc.) and in their characteristic scales (from the millisecond to the century)—as a rope is made of several threads, themselves composed of many thin and short fibers.

The strategy of science, for the last centuries, has been to deprive as much as possible this living time of its manifold qualities so as to reach the elementary and abstract time of physics. The objective has then been to endow anew time, according to the considered domain, with such or such of its confiscated qualities by 'explaining' them, starting from the nature of the systems under study and their specific complexities. This founding difference, too often tacit, between the theoretical concept of time in physics and the empirical notion of time in common practice lies at the root of the misunderstanding between Einstein and Bergson at their famous meeting in 1922—a true dialogue of the deaf, each one being concerned only with his 'own' time. The clearest example of this procedure whereby physics endeavors to enrich its idea of time after having impoverished it is given by the treatment of irreversibility, introduced as a 'secondary quality' of time and justified by statistical arguments, at least for sufficiently large systems, and not without subtleties and difficulties. For all its successes, this strategy leaves open some deep questions. Is it not worthwhile, then, to ask the question of other possible formalizations of temporality, and to look for alternatives to its conventional mathematical representation by the set of real numbers. Could it be useful, if only for phenomenological reasons, in some domains (life sciences, for instance), to set up a notion of time incorporating right from the beginning some of these properties which we usually try to restore at the end? Can one imagine nontrivial mathematizations describing a time intrinsically irreversible? A time with fuzzy instantaneity? A threaded and thick time? The stumbling block on the road toward such accomplishments could well be the prejudice of our traditional representation of time which assimilates it to space. For the 'axis of time,' after all, is but a spatial line, of which we no longer question the metaphorical relevance when tracing it on those familiar diagrams, train schedules or Einsteinian world-lines. Such schemes, spatio-temporal ones from a conceptual standpoint, become spatiospatial as soon as they are laid down on the geometrical plane of the sheet or blackboard, where the time axis is represented by a space axis. Let us not forget, then, that we deal here with convenient procedures of visualization, pictorial metaphors, graphical conventions, with intrinsic limitations. It might well be the case that this privilege given to space, even when the description of time is at stake, derives from our nature as mobile and visual beings; the fact is that our spontaneous estimates for distances are much better than for durations, and our sophisticated theorizations probably rely on the same perceptual foundations. What could be the representations of space and time elaborated by a hypothetical species of intelligent beings, blind and immobile, but sensitive to acoustic and chemical effects, for instance?

A possible line for a first and modest approach, staying within the framework of conventional theoretical physics, would consist in starting not from space and time, but from space and motion as primary notions. In other terms, instead of considering motion as a space change in time, one would consider time as a descriptor of motion in space, and see whether a more flexible conceptualization might emerge from this point of view. Besides, such an approach is a rather operational one, as time is indeed measured by such a process, namely the spatial observation of a motion, whether it be simple (the hands of a clock) or complex (the numbers on a digital screen). In fact, we would only take up Aristotle again, and his deep idea that "time is the number of motion."

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