Annales de la Fondation Louis de Broglie,
Vol. 11, n° 1, 1986

Irreversibility in deterministic physics

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(manuscrit reçu le 2 Décembre 1985)

Abstract : The problem of irreversibility in physics, that is, the "arrow of time", is discussed in the light of the deterministic approaches of Newton and Einstein. Several standard examples that are conventionally used to demonstrate that irreversibility is fundamental in the context of probabilistic, nondeterministic physical theories are discussed here from the viewpoint of nonprobabilistic, deterministic ideas.

Résumé : Le problème de l'irréversibilité en physique, c'est-à-dire de la "flèche du temps", est discuté à la lumière des approches déterministes de Newton et d'Einstein. Plusieurs exemples standard qui sont utilisés habituellement pour démontrer que l'irréversibilité est fondamentale dans le contexte de théories physiques probabilistes et non déterministes, sont discutés en adoptant le point de vue déterministe, non probabiliste.

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*I wish to dedicate this article to the memory of P.A.M. Dirac (1902-84) - the man and his intellectual attitude.

A question that has been posed continuously in physics and chemistry, from the latter part of the nineteenth century until the present time is the following : How is it that on the one hand, when a complex system is left on its own in a non-equilibrium state, it is always seen to evolve time-irreversibly toward the equilibrium state, where it remains, while on the other hand, the dynamical laws of the material constituents of the system (classically or in quantum physics) that govern their motions, are time-reversible ? That is, in view of the time-reversibility of the solutions of the equations of motion for the constituent material elements of a complex system, why is it that we never see it return (when left on its own) to its initial, non-equilibrium state ?

The conventional answer to this question evokes the second law of thermodynamics. This law entails an assertion about the time evolution of the entropy of a complex system, from the time when it was in an (unnatural) nonequilibrium state to the final time when the system had reached equilibrium, corresponding to its maximum entropy. The entropy of the system, in turn, is taken to be a measure of its disorder. Thus the assertion of the second law of thermodynamics is that at equilibrium the most probable state of the multicomponent system of material constituents is the one with maximum disorder.

Therein the probability concept appears in an attempt to *explain* the empirical facts about the irreversibility of physical processes -that is, the so-called "arrow of time". This probabilistic model of entropy was inspired by the pioneering researches in the nineteenth century by Boltzmann and others, that succeeded in identifying the empirically valid (phenomenological) laws of thermodynamics with a particular sort of probability calculus. It is a model that the nineteenth century researchers, Loschmidt[1] and Zermelo[2] assumed contextually in their paradoxical conclusions about the irreversibility of physical processes of complex systems.

In modern times, interesting attempts have been made to explain the irreversibility of processes in the quantum domain, as perhaps fundamental to the explanation for

"time's arrow", generally. Lochak[3] has presented excellent discussions of the approach of the de Broglie group, whereby the attempt is made to identify the arrow of time with the dynamics of the irreversible transitions between the quantum states of matter in microdomain. This is investigated in terms of sufficiently generalizing Schrödinger's wave mechanics so as to include extra terms that may not be time-reversible -thus generalizing the formal expression of wave mechanics to include the irreversible transitions between quantum states where the earlier form was only descriptive of the stationary states of a microsystem.

Prigogine's research program also goes in this general direction, where the attempt is made to formally fuse the entropy concept within the framework of the algebra of quantum field operators. In this approach, irreversibility enters in terms of a nonfactorizable 'superoperator', as representing the measurement of unidirectional time,[4] then identified in a fundamental way with the entropy of the second law of thermodynamics.

These approaches of introducing irreversibility into physics as a fundamental dynamical feature, within the context of a probability calculus and concepts of chaos, stochastic processes, etc. may indeed be the true approach toward the resolution of this problem. But is it a unique explanation for the empirically observed irreversibility of the physical processes of complex systems in nature ?

That is to say, is it not possible that an alternative model that does not at all entail the concepts of probability and chaos could equally explain the physical facts about irreversibility ? I believe that earlier determinists, such as Newton and Einstein, even if they would have been aware of all of the accumulated discoveries in physics to this time, would not have accepted the notion of the elementarity of the probability concept to *explain* any of the facts of nature.

What I mean by the term "determinism" is that a system is *predetermined* in terms of an ordered set of relations. In Newton's physics (based on the atomistic concept

and action at a distance) the ordering parameter was an absolute time measure. But in Einstein's physics (based on the continuous field concept) it could not be generally so, since here time, per se, is a subjective (frame-dependent) measure. Instead of time, per se, the ordering parameters in Einstein's relativistic field theory of matter must be the complete set of space-time parameters (a four-parameter set), rather than the single parameter set, to order the predetermined nature of the system. However, in both cases -in Newton's classical atomistic model of a complex system and in Einstein's field model- the entire material system in *closed*, thus its physics is *predetermined*. This is in contrast with the open system one evokes in defining the entropy concept.

In concurring with the philosophical view of a predetermined system (of Newton or Einstein) I should add that, nevertheless, I fully accept the second law of thermodynamics as a correct aspect of the *descriptive* part of a theory of a complex system. However, in the light of the deterministic approach of Newton or Einstein, I wish to question its use as *explanatory*. It is my contention that in this case statements about probabilities and order-disorder for irreversible process in nature are indeed subjective, based on an observer's particular knowledge of a complex system, rather than objective statements about the underlying causes for the empirical facts about irreversibility.

The use of the entropy concept to *explain* time-irreversible processes in nature seems to me similar to Aristotle's "explanation" for the fall of an object from an elevated position by stating that the 'ground level' is the more natural place for the object to be, if it is material. But we all recognize that it was a giant step for physics when Galileo and Newton *explained* the fall of the material object in terms of precise, objective laws, relating to the causes of the motions of the objects due to their interactions with the matter of the earth (leading to Newton's discovery of his law of gravity, in this case).

The reason that a ball rolls down a hill and does not roll up again, even though there is such a time-reversed

solution of Newton's equations of motion, is that it would take work from the outside (against the action of gravity) to establish the precise boundary conditions that would project the ball back up the hill, to its starting point at the top. Most physicists would certainly agree with this conclusion.

Let us then extend this one body problem to the discussion of a complex system that evolves irreversibly in time, presenting the idea that the *explanation* for the irreversible behavior of the components of this system may not at all be based on ideas of order and disorder, but are rather similarly rooted in *predetermined* mechanical processes, not out of step with the rest of deterministic physics. The order-disorder 'explanations', with the use of the second law of thermodynamics, are considered here in an entirely different context -one that is purely descriptive rather than explanatory.

Example 1. Consider a large basket, containing the order of 10^{24} tennis balls, emptied at the top of a hill. The balls would then all roll to the bottom of the hill, each colliding with blades of grass, pebbles, some with each other, and all eventually stopping at seemingly random locations at the bottom of the hill. Why don't all of these tennis balls ever roll up the hill again, reversing their original paths and winding up in the basket that originally held them ? The determinist's answer is that for this to happen, a certain amount of work would have to be done *from the outside* (or, as Newton would have said, *external* forces would have to be exerted) in order to set up the proper boundary conditions on each of the tennis balls (including recovering the energy lost in friction on the hill, etc.). The fact that the tennis balls do not move up the hill to their original positions in the basket is then a matter of the missing elements of the dynamics ; it is not a matter of processes that go from disorder to order, in fundamental terms. The only 'disorder' in this process was the *lack of knowledge* that an observer had about the detailed behavior of each of the 10^{24} tennis balls.

Of course, this does not mean that the description

in this example of a great many tennis balls rolling down a hill, in terms of order and disorder, is false. It only means that the latter description in terms of entropy flow answers a different sort of question about the system than the question posed in the fundamental dynamical explanation for the many-body system.

It is similar to this familiar situation : Given the initial conditions of position, torque, initial velocity, etc. of a flipped coin, and the complete interaction of this coin with the earth, the air molecules it encounters as it flip-flops up and down again, there is a predetermined path for this coin, that in principle one obtains by integrating the correct equation of motion, and this unique solution then predicts precisely whether or not it will land heads. But in another context, one may ask : What is the probability that the coin will land heads ? The answer to this question is 1/2 -because we know in advance that there are two (equally weighted) possibilities. The point is that the theory of probability that we just used does not at all *explain* the behavior of the coin in time ! It is not a fundamental theory of the temporal behavior of the coin. Rather, it is purely *descriptive*, and useful for an observer.The probability theory deals with the subjective aspects of this example while the dynamical theory deals with the objective reality. That is, the behavior of the 10^{24} tennis balls rolling down a hill, or the behavior of the flipped coin, are in terms of predetermined trajectories that are indeed independent of the knowledge or lack of knowledge of any human (or non-human) observer ! This is the axiomatic starting point of a deterministic theory.

Example 2. Consider the following famous example that does not entail gravity : A dark blue drop of ink is released into a colorless liquid in a beaker, in a gravity-free domain, say in outer space. One should then observe the diffusion of the components of the ink drop into the liquid in the beaker until the drop, as such, disappears and the entire liquid has turned a pale blue, uniformly. The question is then asked : Why is it that we never see all of the ink molecules in the beaker retrace their original paths to form the initial ink drop, in view of the time-reversed solutions of the equations of motion?

I believe that the answer to this question is the same as it was in the preceding examples -that it would take work from the outside to set up the precise initial conditions for each of the ink molecules so as to have them re-trace their original paths, including each of their collisions with the clear liquid molecules of the original diffusion.

The reason that the ink drop broke up in the first place was not anything to do with fundamental order and disorder ; it was rather that the forces acting on the drop by the host liquid that surrounded it caused the drop to be in an unstable state, energetically, just as the earth's gravity field caused the tennis balls in the preceding example to be in an unstable state when they were at the top of the hill. In both cases, of the tennis balls and the ink drop, the surroundings interacted with the system causing it to evolve to a stable configuration (i.e. minimum energy). To restore the initial unstable configuration must then require external work in order to set up the boundary conditions on each of the elements of the respective complex systems that would lead to their time-reversed trajectories. That is to say, the *reason* for the lack of observation of the restoration of the initial (unstable) situations is one of dynamics, it is not a reason having to do with processes of restoring more order from less order in the respective systems.

Example 3. Consider the example of the radioactive decay of a macro-quantity of radium. Does this process not necessarily entail a fundamental change from order to disorder ? Empirically, one does observe a seemingly random emission (in time) from the radium sample, observed as a random distribution of pulses of the decay products as they are detected in, say, a Geiger counter, as : | | | | ..... But do we have any guarantee that these signals are not in actual fact connected (below the experimenter's arbitrarily set voltage bias), as the peaks of a coherently connected curve ? If we should then consider the *closed system* that entails the radium and its decay products, as well as the environment that they interact with, an objective theory might prescribe that a predetermination of the respective paths of the radium nuclei and its decay products must follow. Again, 'disorder' per se in this example would

only be a matter of the 'knower's' lack of awareness of the exact state of the entire system at any particular time. But in this view, there should be a fundamental order that *underlies* the process of radioactive decay, independent of anyone's personal knowledge of it. Thus, to restore the original radioactive nuclei (the initial unstable state) external work would have to be done on the stable system of decay products in order to establish the proper boundary conditions on these elements so as to cause them to retrace their original paths, back to the initial (nonequilibrium) state of the unstable radioactive nucleus. What I am saying here is that the empirical facts about radioactivity do not compel us to *explain* the process in terms of *fundamental disorder*, though a *description* with these concepts would certainly be useful for the scientist, in the same sense that it is useful to use probabilities to claim that the chance that a coin will land heads is 1/2.

Example 4. What about the irreversible aging of a human body ? I believe that this process is similar, in principle, to the preceding examples of observed irreversibility. The aging of our bodies is a matter of cellular decay wherein our biological molecular structures change, apparently irreversibly. But in principle, by supplying the appropriate external work to return the atomic constituents of our biological molecular make up to their previous configurations (that made up the youthful body !), we should be able to recover the earlier states of our bodies. It is only that with our present state of knowledge it would be extremely difficult to become aware of all of the boundary conditions and then to supply them in order to carry out such a process. The idea is that our bodies do not return to their youthful states *on their own* because such boundary conditions on the atomic constituents of our life systems are not supplied spontaneously. This is not a matter of a fundamental explanation in terms of violating the second law of thermodynamics. That is, the explanation for the fact that our bodies do not become youthful on their own is in principle the same reason that the ball at the bottom of a hill does not roll up again on its own, even though there is such a time-reversed solution of Newton's equations of motion.

The example of irreversible aging is the same as

the situation in which a pool player breaks up an arrangement of pool balls in a triangular configuration at one end of the pool table, scattering them in all directions due to a collision with the cue ball. It is unlikely that a second collision between the cue ball and one of the pool balls would be able to scatter all of the rest of the pool balls back into the initial triangular configuration because such a process would not normally set up the boundary conditions to time-reverse all of the trajectories of the pool balls on the table. To accomplish the latter would take external work that would correspond to increasing the total configuration energy of the system. It is not a matter of order and disorder in fundamental terms. In principle, then, this process could be carried out without violating any of the fundamental laws of physics.

A third example similar to these is that of a deck of cards, before it is shuffled. Initially these cards are arranged according to suits and in sequence of numbers, ace to ten, Jack, Queen, King. A thorough shuffling would then destroy all of that order. To restore it by reshuffling again would then require the external work necessary to set up the proper boundary conditions on each of the 52 cards that would send them to the proper place in the ordered deck. That is, I see this example as no different in principle from the preceding examples, whereby an *explanation* for the configurations of the cards had to do with predetermined trajectories and not with questions of order and disorder. The latter are only useful *descriptive* elements for the complex system in the same sense that we *use* a probability calculus to conclude that the chance of the coin landing heads is 1/2.

Example 5. Finally, consider the problem of irreversibility in the present day cosmological problem. It is claimed by most contemporary astrophysicists that the universe is expanding without limit, starting at an initial 'big bang' (about 15 billion years ago) when there was maximum order (minimum entropy) toward the indefinite future when all of the stars will have burned out and the entire universe will be interstellar dust, corresponding to the equilibrium state and maximum disorder (maximum entropy).

Whether or not this single big bang model is a phy-

sically valid cosmological model, the determinist's *explanation* for this process of expansion must be in objective terms, rather than in terms of the subjectivity of the process of entropy change. That is, when the universe as a whole will become more and more populated with interstellar dust, and correspondingly less and less containing condensed stars, any observer would of course have less awareness of the precise locations, speeds, etc. of the constituent elements of the universe. But the *explanation* for the distributions of the elements of the material universe would still be the fundamental forces that control the whereabouts and other physical properties of these things of the universe -whether or not any human consciousness is aware of them ! I believe that Newton would have replied in this way, even if he would have been made aware of all of the astronomical evidences that have been discovered since his day. That is, I do not think that the present day cosmologists who rely on the law of entropy change as a part of a fundamental *explanation* for the behavior of the universe as a whole would have made their case with Newton.

On this point, I believe that Einstein was in full agreement with Newton. They both would have accepted irreversible thermodynamics as an important *descriptive* part of the representation of the system of matter that is the universe, in terms of probabilities and our conscious awareness. But I feel quite certain that they would not have accepted the entropy law, the role of fluctuations and chaos, etc. as having anything to do with a fundamental (objective) *explanation* of cosmological evolution.

This seems to me to reduce to the main question in the debates between Bohr and Einstein, as to whether the laws of nature necessarily entail some irreducible subjectivity, or whether there is an objective universe with accompanying laws of matter that are independent of whether of not human beings are there to observe its physical manifestations[5]. This is indeed the well known controversy in epistemology between *positivism* and *realism*, as to which is the more valid approach to the achievement of our knowledge of the universe.

Summing up, the questions remain : Do the empiri-

cal evidences regarding irreversible processes in nature *compel us* to adopt a probabilistic theory for their explanation ? or is it possible that a deterministic model, such as Newton's atomistic ontology or Einstein's continuum field ontology, could explain (perhaps more accurately) these observations ? I do not believe that the present-day facts about irreversibility conclusively rule out the deterministic point of view (in the sense of a predetermined universe). On the historic debates between Bohr and Einstein regarding the future course of physics, as to whether it will uphold the nondeterministic or the deterministic points of view, perhaps Dirac was correct in his recent statement[6] :

> "... I think it is very likely, or at any rate quite possible, that in the long run Einstein will turn out to be correct".

REFERENCES

1. J. Loschmidt, Wien. Sitz. 73, 139 (1876) ; 75, 67 (1877).

2. E. Zermelo, Ann. Physik 57, 585 (1896) ; 59, 793 (1896).

3. G. Lochak, Found. Phys. 11, 593 (1981) ; in *Dynamical Systems* (Springer-Verlag), ed. S. Diner, D. Fargue and G. Lochak, in press.

4. B. Misra, I. Prigogine and M. Courbage, Proc. Nat. Acad. Sci. (U.S.A.) 76, 4768 (1979).

5. See the article by N. Bohr and the reply by A. Einstein in : P.A. Schilpp, ed., *Albert Einstein - Philosopher-Scientist* (Library of Living Philosophers, 1949).

6. P.A.M. Dirac, in : G. Holton and Y. Elkana, ed., *Albert Einstein - Historical and Cultural Perspectives* (Princeton, 1982), p. 86.